GROUND-TRUTH COLLECTION FOR MINING EXPLOSIONS IN NORTHERN FENNOSCANDIA AND RUSSIA

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ABSTRACT

This project is providing ground-truth information on explosions conducted at the principal mines within 500 kilometers of the ARCES station, and is assembling a seismic waveform database for these events from local and regional stations. The principal mines of interest are in northwest Russia (Khibiny Massif, Olenogorsk, Zapolyarny, and Kovdor groups) and Sweden (Malmberget, Kiruna). These mines form a natural laboratory for examining the variation of mining explosion observations with source type, since they include colocated surface and underground mines and mines conducting a variety of different shot types. In September 2002 we deployed two lines of temporary stations from the Khibiny Massif through and to the north of the ARCES station. This deployment is producing data that will allow researchers to examine the variation of discriminants caused by varying source-receiver distance and the diversity of explosion types.

To date, we have collected ground-truth information on 1,118 explosions in the Kola Peninsula, and have assembled waveform data for approximately 700 of these. The database includes waveforms from instruments temporarily deployed in the Khibiny Massif mines, from the Apatity network just outside of the Massif, from LVZ, KEV and ARCES, and from the stations deployed along the two lines into northern Norway. In this paper we present representative waveforms for several types of shots recorded at various regional distances.

We have conducted a preliminary study of the variation of phase ratios as a function of source type. This study shows significant differences in Pn/Sn and Pn/Lg ratios for two types of mining explosions: surface ripple-fired explosions and compact underground explosions. Compact explosions are, typically, underground explosions of a few tons with only one or two short delays, and are the closest approximation to single, well-tamped explosions available in the Khibiny mines. The surface shots typically are much larger (ranging up to hundreds of tons), with many delays. The surface mine that we present results for typically also conducts several distinct shots across the mine nearly simultaneously (with a few seconds or tens of seconds). Measured phase ratios are more consistent for compact underground explosions. This consistency is an expected result given the smaller scope for shot variation in these smaller events. In addition, Pn/Lg ratios appear more stable than Pn/Sn ratios for both types of events. The most interesting result is that the compact underground explosions are richer in shear energy (i.e. having smaller P/S ratios) than their surface ripple-fired counterparts.

We continue to work on an approach for identifying the principal mines to be targeted for screening at a particular station. Often, routine industrial blasts constitute a large proportion of events detected by monitoring stations close to major mining districts. Many mines may be present, and it may be a problem to determine which subset of mines is responsible for the majority of the events, and should be prime candidates for the deployment of ground-truth collection resources. Our solution to this problem entails several steps. The first is to find geographic clusters of events that may correspond to major groups of mines. For this step, we use event density maps generated from existing network catalogs. This year we examined some of the tradeoffs in generating event density maps: use of automated bulletins to produce maps vs. analyst-reviewed bulletins, and the amount of time required to produce stables maps which can be used to identify significant mines.

OBJECTIVES

This year the project has had five principal objectives:

1. Collect ground-truth information for a large number of explosions in a diverse set of mines in the Kola Peninsula.
2. Assemble a database of waveform observations of these events from principal monitoring stations of the region.
3. Deploy additional stations in the region to fill range gaps in the set of observations.
4. Perform preliminary analysis of the variation of standard discriminants with source-receiver range and source type.
5. Examine strategies for allocating ground-truth resources in complex mining regions.

RESEARCH ACCOMPLISHED

Ground-truth Collection and Database Construction

KRSC has collected ground-truth information on mining explosions in the Kola Peninsula for the period September 2001 through June 2003. Information provided by the operators of ten mines in northwest Russia (Figure 1) includes shot location (i.e. which mine), the type of each shot (underground, surface, ripple-fired, compact), the yield, and the number of shots (where several are nearly simultaneous). KRSC estimates the origin times of all explosions using its local and near regional seismic network. In addition, KRSC has deployed two temporary stations (RASV, GFR) within the Khibiny Massif complex (Figure 2) and another station near the Olenogorsk group (MON). Waveform data are available from the in-mine sensors typically for about one third of all the shots.

The GT catalogs provided by KRSC are being processed into an Oracle database and are being used to extract waveforms from continuous data. To date, information on 1,118 events has been loaded to the database (through March 2003). We have extracted event segment waveform data for over 700 of these events (from the ARCES array, the Apatity stations and in-mine stations).

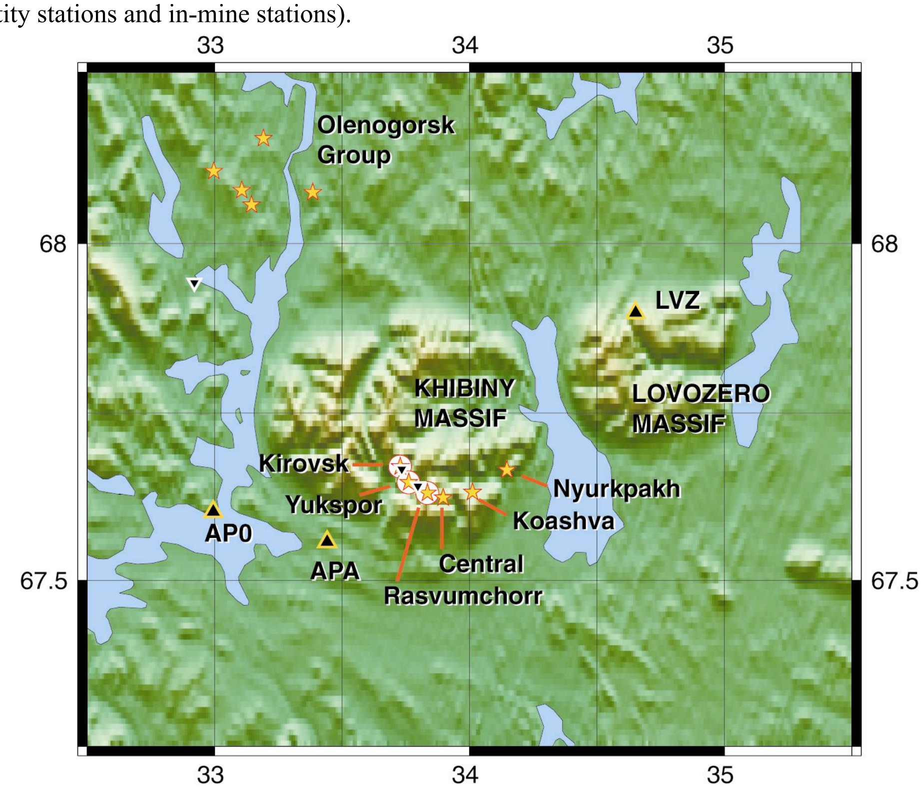


Figure 1. Locations of the mines (stars; circles indicate mines with both underground and surface facilities), permanent stations (triangles) and temporary stations (inverted triangles) in the vicinity of the Khibiny Massif included in this study. The local stations provide origin times for the explosions.

Temporary Sensor Deployment

To enable studies of the behavior of discriminants over a range of source-receiver distances and source types, we deployed an additional eight stations in northern Finland, Norway and Russia. Six GS-13 three-component stations with Reftek recorders were deployed in late August / early September 2002 (Harris, et al., 2002) to sites in northern Norway and Finland. Subsequently a broadband station with a Reftek recorder was deployed at the Zapolyarny deep borehole site in Russia. A significant sample of data has been collected from these sites, allowing preliminary analysis. Continued operation of these stations until late summer 2004 is planned.

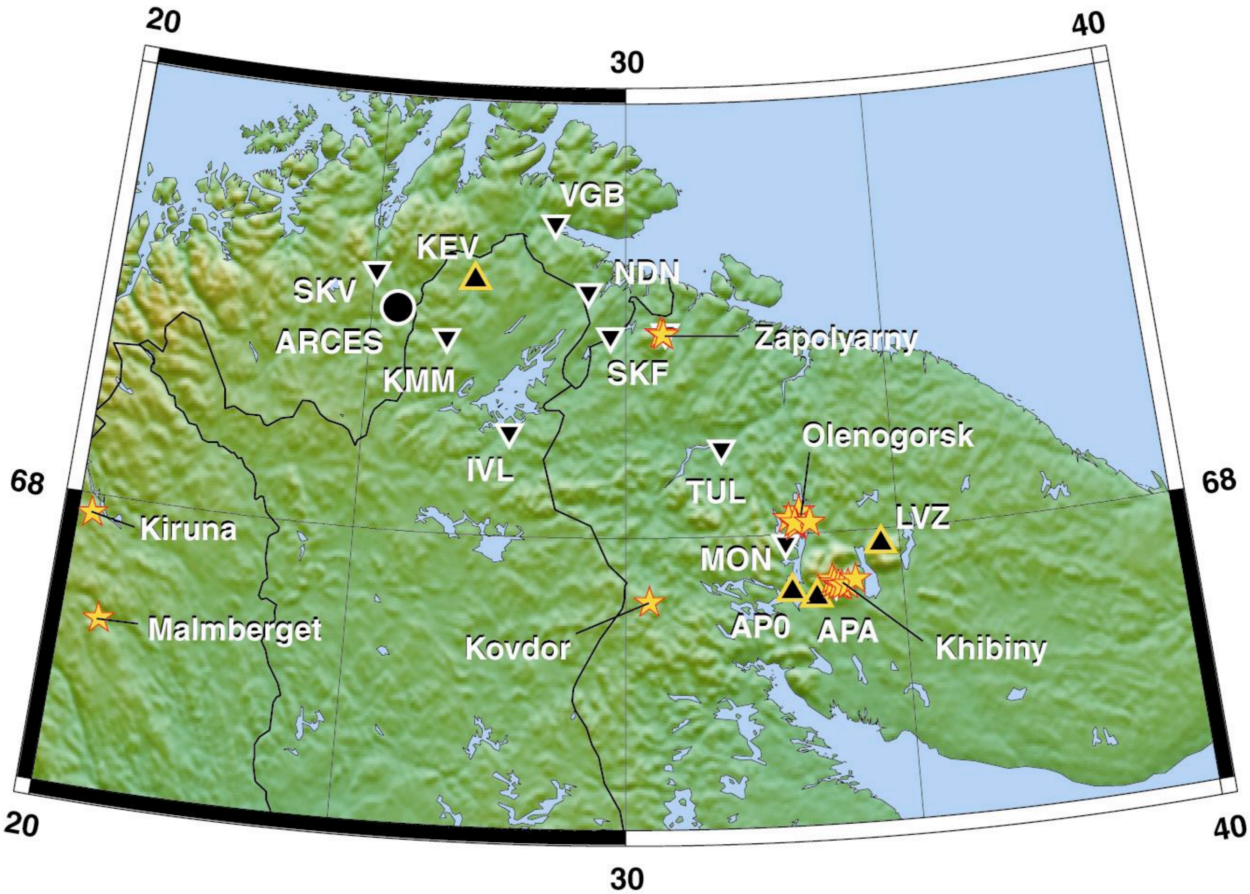


Figure 2. Sites of temporary seismometer deployments (inverted triangles), major mines or mine groups (stars) and permanent stations (triangles and filled circle for IMS primary) included in the regional-scale portion of this study.

Preliminary Examination of Data and Discriminant Behavior

A preliminary examination of the data from the ARCES array and stations along the southern line deployed in Finland and Norway show significant differences in the character of seismic signals from different types of mining explosions. In particular, compact underground explosions at the Kirovsk mine and surface ripple-fired explosions at the Central mine (Khibiny Massif, Figure 1) produce signals with markedly different variability. The compact underground explosions are small shots typically in the 2-5 ton range conducted with only a few delays. The surface shots at the Central mine typically are much larger, ranging up to several hundred tons in the aggregate and with many delays. In addition, the Central open-pit shots are usually conducted in several separate groups and dispersed over the 2-3 kilometer aperture of the mine. These separate shots are typically detonated within a few seconds or tens of seconds of each other.

The signals from the Kirovsk compact underground shots are relatively uniform and consistent with their simplicity. Figure 3 shows a typical Kirovsk compact shot filtered into a succession of 4-Hz bands. At left in the figure are the observations from our temporary station at IVL that show a relatively flat distribution of energy across all frequency bands at a source-receiver range of 271 kilometers. This type of energy distribution is consistent for compact underground shots.

By contrast, the open-pit ripple-fired explosions conducted at the Central mine are relatively inconsistent. Figure 4 shows three examples of surface explosions from that mine. The event in Figure 4a has a very similar pattern to the compact explosion of Figure 3. The event of Figure 4b displays a marked decline in signal energy as a function of frequency (more normal by most analyst's expectations). Figure 4c shows an event where the energy actually increases as a function of frequency. This large range in spectral characteristics undoubtedly is a function of the differences in detail of the delays applied in the shots, as well as the complex interactions among the several groups of shots that comprise each of these explosions.

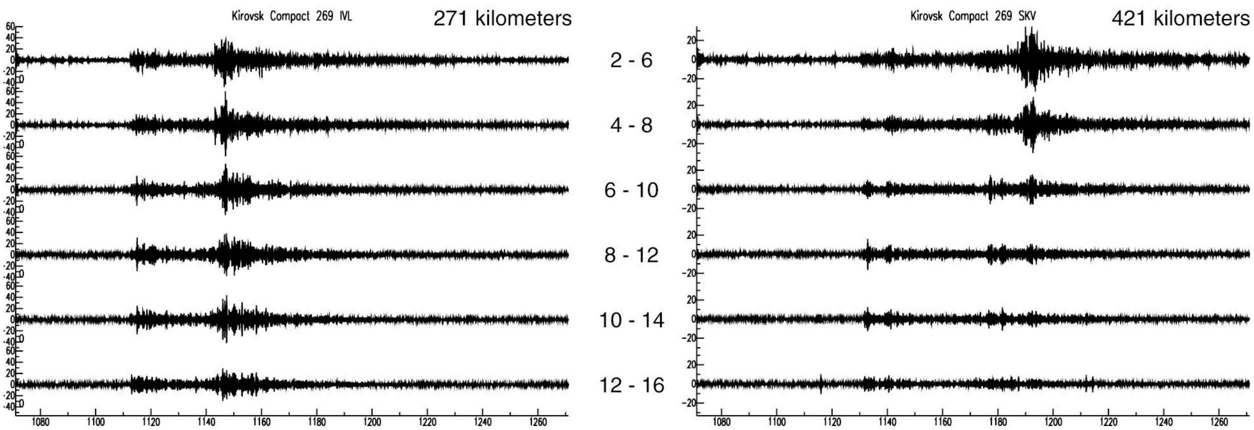


Figure 3. Compact underground explosions conducted at the Kirovsk mine show fairly uniform broadband excitation when observed at IVL (left; 271 kilometer range). These plots display waveforms filtered into overlapping bands of 4 Hz width (2-6 Hz, 4-8 Hz, etc.). This uniform pattern of excitation is consistent for shots of this type. At SKV (right; 421 kilometer range) the larger shear attenuation results in the extinction of the shear phases, Sn and Lg, above 10 Hz.

The behavior of P/S discriminants is consistent with these simple waveform observations. P/S ratios for the compact underground explosions exhibit less scatter than corresponding ratios for the surface ripple-fired explosions. We computed P/S ratios for a selection of Kirovsk and Central events recorded with good signal-to-noise ratios at our temporary stations IVL and SKV (Figure 5). The compact explosions P/S ratios exhibit substantial less scatter, particular when observed at the more distant station (SKV). It is more remarkable that there appears to be a distinct bias between the two types of events. The compact shots have noticeably lower P/S ratios than their open-pit counterparts. This observation is at variance with expectations that smaller underground shots with few delays might be a better approximation of single shots such as nuclear explosions (which should have higher P/S ratios). It is possible that this unexpected behavior is due to the fact that the compact underground shots are typically designed to drop the ceilings of tunnels. Consequently, they are not well contained (despite being underground), and they may have large secondary energy releases from the mass of the falling ceiling.

Note that the P/S ratios increase with increasing frequency, which is consistent with the frequent observation that P/S ratios discriminate earthquakes and explosions more reliably at higher frequencies. Pn is the more suitable P phase to measure, given its lower increase in attenuation rate with increasing frequency, as has been noted previously (Kvaerna, et al., 2002). Similarly, Sn is more likely than Lg to be observed at greater distances and higher frequencies (Kvaerna, et al., 2002).

These measurements were repeated with larger numbers of event observations available at ARCES, with the same results. From the database we have been constructing, we selected 66 Central open-pit explosions (with good SNR at ARCES) and 185 Kirovsk compact underground explosions. The P/S ratios in two frequency bands are shown in

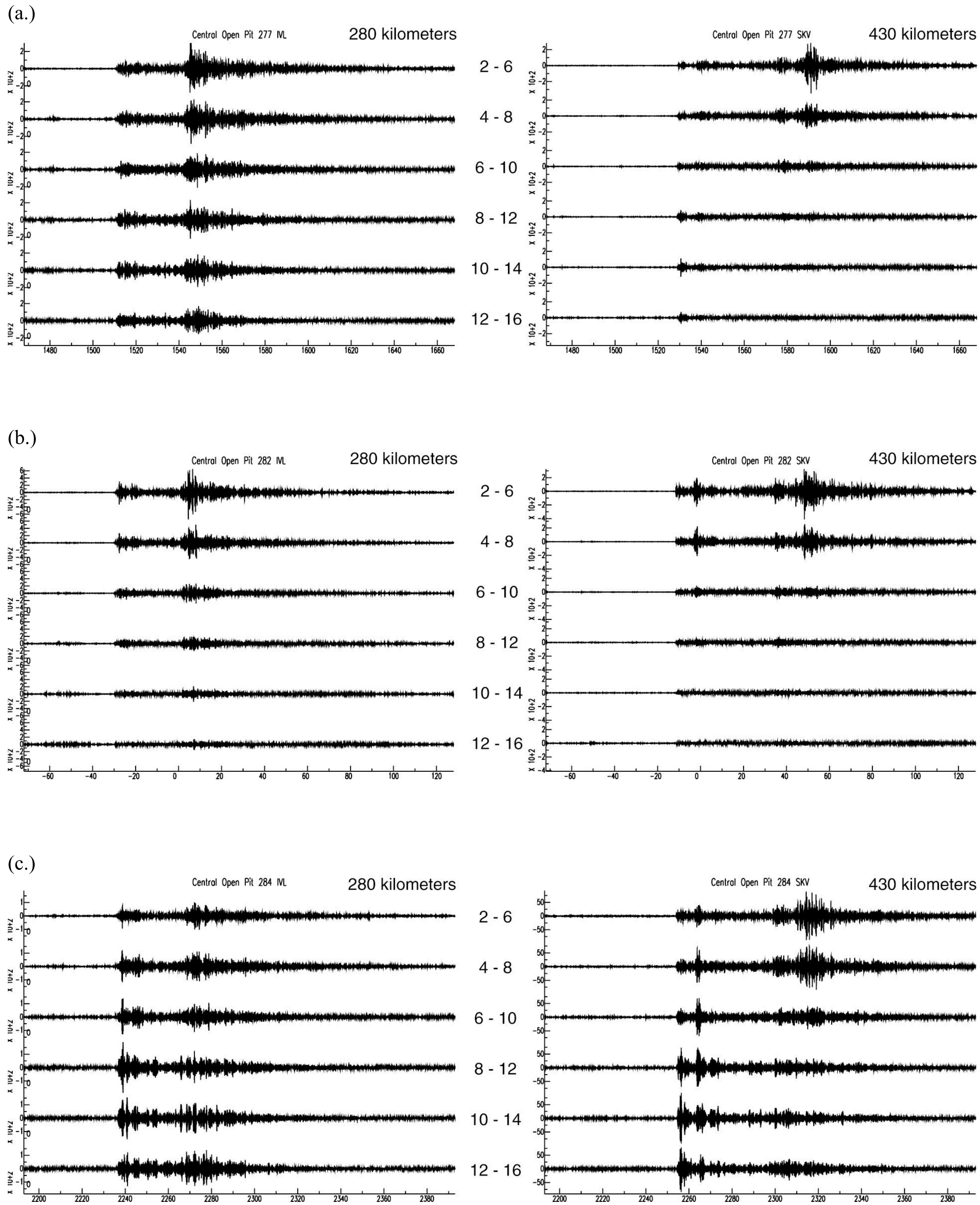


Figure 4. Larger ripple-fired explosions at the Central open-pit mine of the Khibiny Massif exhibit large variations in spectral content consistent with their greater complexity. Signals energy content may be flat (a.) with frequency, or may decrease (b.), or increase (c.) as observed at station IVL (left). The variations are even more pronounced for P phases observed at SKV (right).

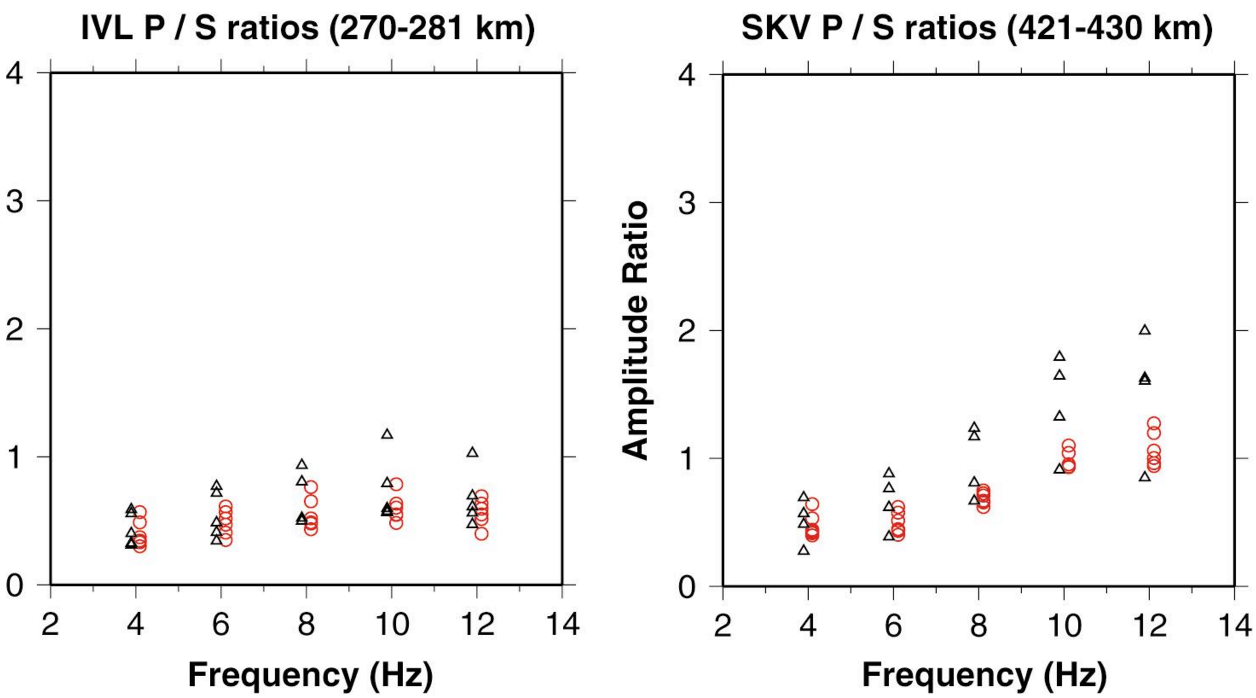


Figure 5. P/S ratios for open-pit explosions (triangles) show more scatter than P/S ratios for compact underground explosions (circles). Ratios for the compact underground shots are biased lower than their open-pit counterparts. These effects are more pronounced at greater source-receiver distances.

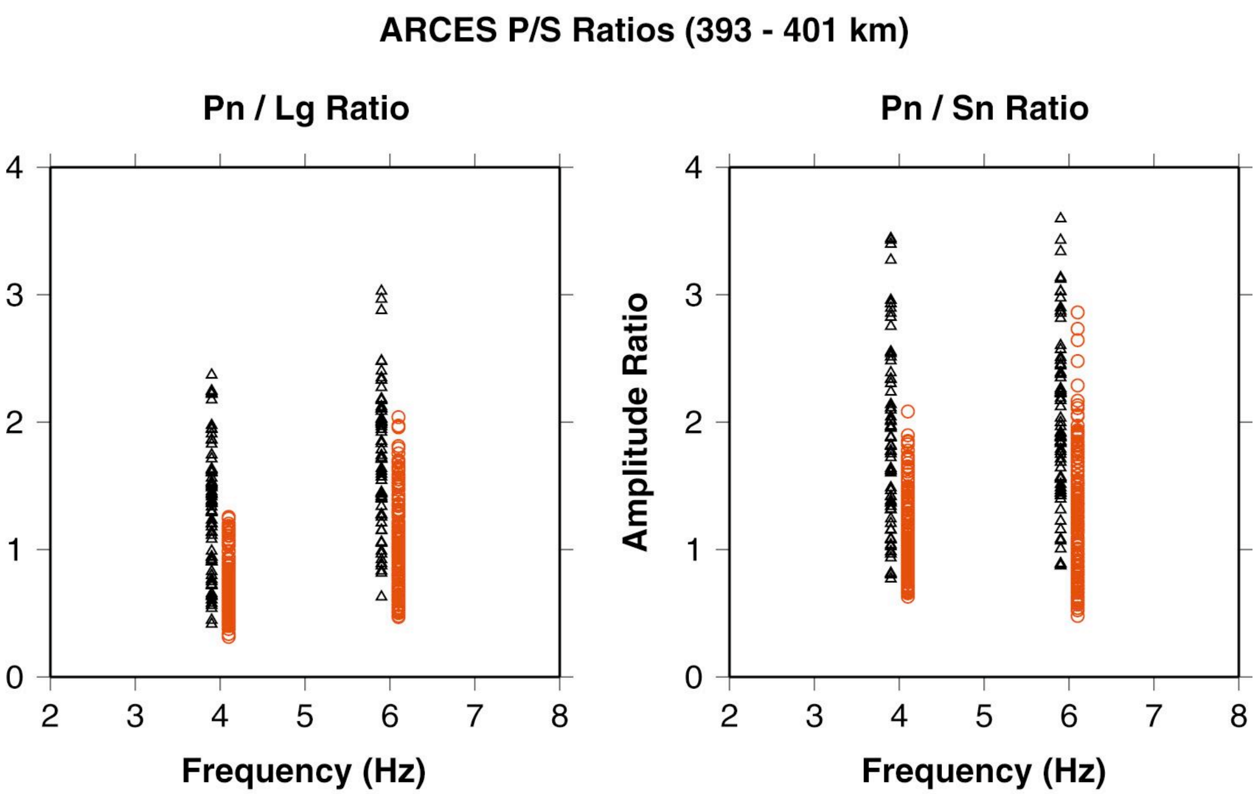


Figure 6. Plots of larger populations of compact underground (185, circles) and open-pit (66, triangles) P/S ratios show the same trends at ARCES as at the temporary stations. The Pn/Lg ratio (left) is more stable than the Pn/Sn ratio (right).

Figure 6, this time separated by shear phase type (the Figure 5 measurements used a shear window that encompassed both Sn and Lg). For these measurements, we used one of the short-period array elements, so that measurements could be conducted only in the two lowest frequency bands (2-6 and 4-8 Hz). Note that the Pn/Lg ratios have lower variance than the Pn/Sn ratios.

Strategies for Ground-truth Allocation

One approach to allocating ground-truth resources is to determine which mines or mining districts are most visible seismically. Maps of seismic event density, constructed from catalogs, provide one method for determining the hot spots requiring calibration attention. This year we examined several tradeoffs in the construction of event density maps: use of single-station catalogs vs. network catalogs, use of automated catalogs vs. analyst-reviewed catalogs, and use of catalogs constructed over short time durations vs. long time durations. In the last case, we seek to answer the question "How much data is enough?"

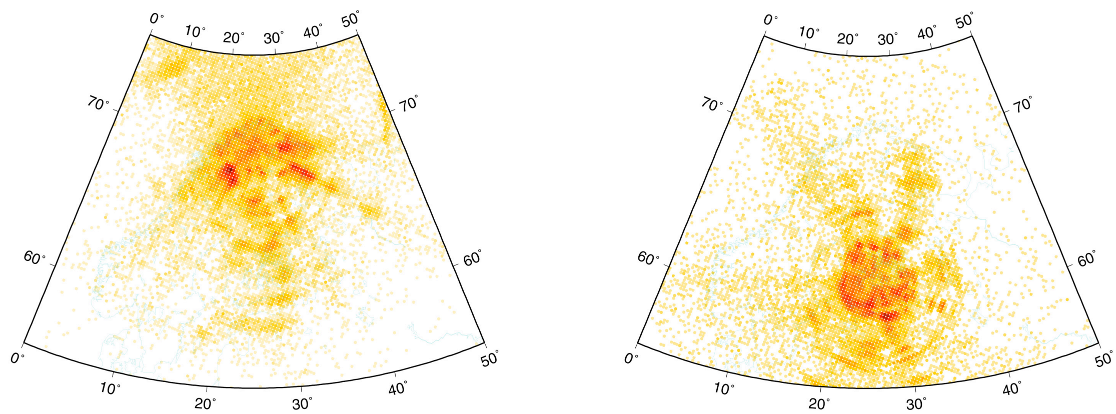


Figure 7. Event density maps constructed from automatically-generated single-station catalogs of about one decade duration. The event density map at left is constructed from an ARCES catalog, and the one at right is constructed from a FINES catalog. These maps have a high degree of clutter and poorly resolved geographic clusters, but do serve to identify some of the major mining regions. Areas of greatest event density are red (dark), grading to yellow (light) for intermediate density, then white for low event density.

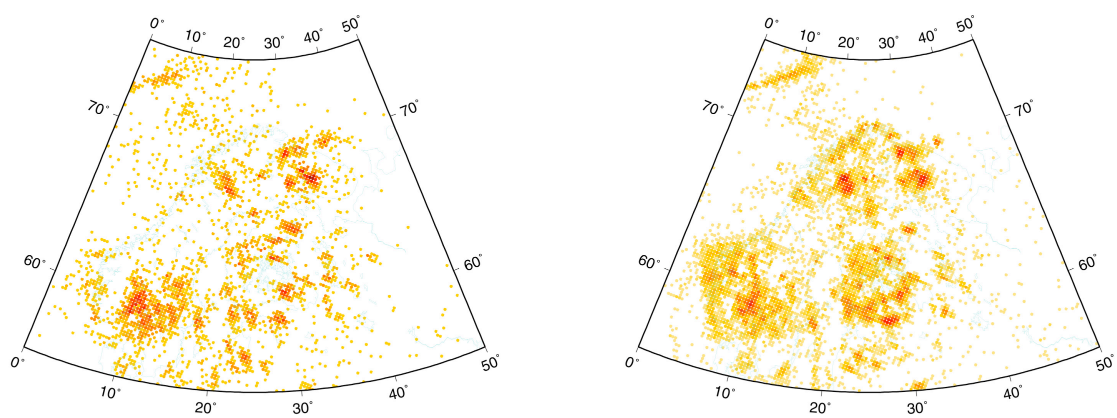
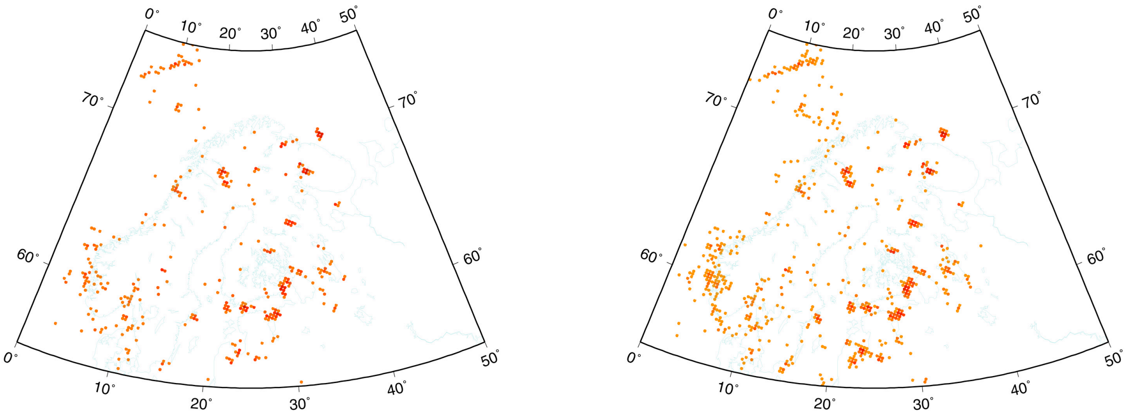


Figure 8. Event density maps derived from network catalogs are far better resolved with less clutter than maps constructed from individual station catalogs. At left is a map derived from the automated NORSAR global beamforming catalog; at right is the map developed from the analyst-reviewed EPX bulletin. The latter bulletin spans a decade.

Figure 7 shows event density maps constructed from automatically generated bulletins for individual stations, ARCES at left and FINES at right. These maps are poorly resolved with a large amount of background clutter. They might suffice to identify the very largest mining districts within 300 or 400 kilometers of the station. A much more satisfactory solution is to use event density maps generated from network catalogs. We show two such maps in Figure 8. At left is an event density map derived from the NORSAR automatically-generated global beamforming bulletin. This map has excellent delineation of large mining districts (Khibiny, Olenogorsk, the two Swedish iron mines, etc.), but still a moderate amount of background clutter. The map at right was produced from the highest-quality analyst-reviewed NORSAR bulletin and has even better resolution and further reductions in clutter. Clearly network bulletins are required to produce adequate maps for identifying high-interest mines or mining districts, and analyst-reviewed bulletins are desirable.



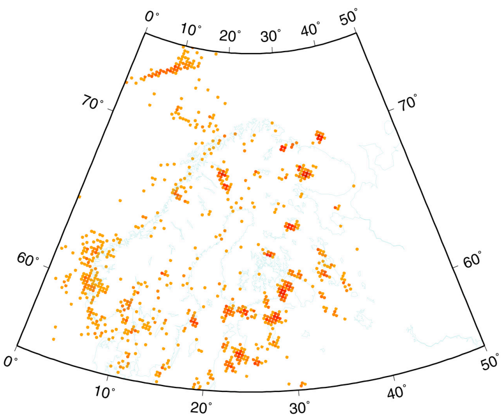


Figure 9. Event density maps produced from the NORSAR analyst-reviewed EPX bulletin using just one year of data (upper left), two years of data (upper right) and three years of data (lower left). All three delineate the major mining groups of the region, though the smaller mining regions of the Baltic states are only resolved with two or more years of data.

Figure 9 provides some insight on how much data is required to delineate significant mining areas. The figure shows three maps constructed from one, two and three years of the NORSAR analyst-reviewed network bulletin. The major mining groups are delineated with just one year of data, though many of the smaller mining districts require two or more years to be resolved from background clutter.

<u>CONCLUSIONS AND RECOMMENDATIONS</u>

The bias in spectral ratios between compact underground explosions and open-pit ripple-fired explosions has potential operational and source phenomenology implications. P/S discriminants that lump all mining explosions together may have higher variance than a collection of discriminants designed to sort the different types of shots.

The potential reduction in variance may become more significant as P/S discriminants are adapted to higher frequency signals. The fact that compact underground shots appear relatively richer in S energy than surface rippled shots may shed light on source physics, especially the generation of S phases. Not only is there a clear observational difference in the relative generation of P and S phases in these two populations of mining explosions, but we also have information on how these two shot types are conducted.

Our first recommendation for continued research is to check the reproducibility of the P/S bias observation for other mines. The Rasvumchorr mine conducts compact underground explosions, and the Koashva mine conducts large ripple-fired surface shots. Kirovsk occasionally conducts small surface explosions. The Olenogorsk mines and Kovdor conduct larger ripple-fired surface explosions. Our database contains many examples of these other explosions that can be used to check reproducibility. In addition, a later phase of the project will provide data from the Swedish iron mines at Kiruna and Malmberget, both of which conduct compact underground shots.

Our second recommendation is to determine why the compact underground shots appear relatively richer in S energy. Does it have anything to do with the fact that these shots are subterranean? Is it a function of the fewer delays (i.e. does the large pattern of delays in the surface shots preferentially suppress shear energy)? Is it a secondary mass transfer effect? Many of the smaller underground shots are designed to drop the roof of a tunnel. Some of the data we are collecting will help answer these questions. The Khibiny mines conduct occasional large ripple-fired explosions underground. A combination of observations and modeling probably will be required to understand the source physics. Results from this summer's source phenomenology experiments in Arizona should be particularly useful.

ACKNOWLEDGEMENTS

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